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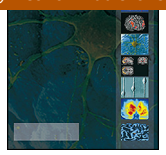

Short communication

Dual-hemisphere transcranial direct current stimulation over primary motor cortex enhances consolidation of a ballistic thumb movement

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HIGHLIGHTS

- Transcranial direct stimulation (tDCS) enhances acquisition of some motor skills.
- We examine the effects of tDCS on consolidation of a newly learned ballistic thumb movement.
- The consolidation is improved 24 h, not 1 h, after dual-tDCS over M1.

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ABSTRACT

Transcranial direct current stimulation (tDCS) is a noninvasive technique that modulates motor performance and learning. Previous studies have shown that tDCS over the primary motor cortex (M1) can facilitate consolidation of various motor skills. However, the effect of tDCS on consolidation of newly learned ballistic movements remains unknown. The present study tested the hypothesis that tDCS over M1 enhances consolidation of ballistic thumb movements in healthy adults. Twenty-eight healthy subjects participated in an experiment with a single-blind, sham-controlled, between-group design. Fourteen subjects practiced a ballistic movement with their left thumb during dual-hemisphere tDCS. Subjects received 1 mA anodal tDCS over the contralateral M1 and 1 mA cathodal tDCS over the ipsilateral M1 for 25 min during the training session. The remaining 14 subjects underwent identical training sessions, except that dual-hemisphere tDCS was applied for only the first 15 s (sham group). All subjects performed the task again at 1 h and 24 h later. Primary measurements examined improvement in peak acceleration of the ballistic thumb movement at 1 h and 24 h after stimulation. Improved peak acceleration was significantly greater in the tDCS group (144.2 ± 15.1%) than in the sham group (98.7 ± 9.1%) ($P < 0.05$) at 24 h, but not 1 h, after stimulation. Thus, dual-hemisphere tDCS over M1 enhanced consolidation of ballistic thumb movement in healthy adults. Dual-hemisphere tDCS over M1 may be useful to improve elemental motor behaviors, such as ballistic movements, in patients with subcortical strokes.

1. Introduction

The acquisition of motor skills plays a fundamental role in daily life. Motor skill learning is the process by which movements are executed more accurately and rapidly as a result of motor training. In general, the effect of motor training occurs not only during training but also afterwards, a phenomenon termed consolidation [1–4]. Consolidation can result in increased resistance to interference (memory stabilization), or even in improved motor performance after training is completed (memory enhancement). These two types of consolidation play important roles in the acquisition of motor skills [2,3].

Transcranial direct current stimulation (tDCS) is a noninvasive technique that modulates cortical excitability via electrodes in humans [5]. Anodal stimulation increases excitability of the primary motor cortex (M1). Previous studies have reported that

Abbreviations: M1, primary motor cortex; tDCS, transcranial direct current stimulation.

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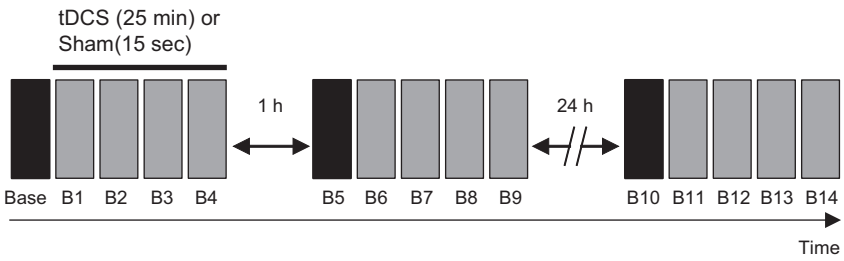

Fig. 1. Experimental design.
After baseline measurements, subjects were trained in a ballistic thumb movement in four blocks (B1–B4) with bilateral tDCS over M1 either for 25 min (tDCS group) or for 15 s at the beginning of training (sham group). Subjects repeated the same training without tDCS or sham stimulation at 1 h and 24 h after tDCS or sham stimulation session.

various motor skill performance is improved in healthy adults and in stroke patients when M1 is stimulated with anodal tDCS [6–15]. In addition, recent studies have shown that tDCS over M1 enhances consolidation of various motor performance tasks, such as visuomotor adaptation [16], serial reaction time [17], and sequential visual isometric pinch [18,19].

Ballistic movements are elementary motor behaviors. For optimal performance of ballistic movements, subjects must direct maximal drive to primary agonist muscles while minimizing drive to antagonistic muscles [20,21]. The electromyographic pattern of a ballistic movement is characterized by two bursts of phasic agonist muscle activity and one burst of phasic antagonist muscle activity. The coordination of reciprocal muscle activation for ballistic movements is one of the fundamental components of fine motor control [20]. It was previously reported that consolidation of ballistic movement skills involves M1 [4]. However, it remains unknown whether tDCS over M1 enhances consolidation of ballistic movement skills.

The aim of this study was to examine whether tDCS over M1 enhances consolidation of ballistic movements in healthy adults using a dual-hemisphere tDCS protocol. Dual-hemisphere tDCS, which excites one hemisphere and inhibits the other, is a powerful strategy to improve behavioral performance [14,22–25]. The mechanisms underlying improved performance observed with dual-hemisphere tDCS may be the combined effect of increased excitability in one hemisphere and decreased excitability in the other, likely via interhemispheric connections [10,14,25]. Interhemispheric inhibition has long been thought of as a "rivalry" between the two hemispheres, with motor function in the cortex of one hemisphere promoted by inhibitory transcranial magnetic stimulation of the contralateral cortex [26].

Therefore, we hypothesized that decreased excitability of M1 in the left hemisphere via cathodal tDCS may further increase M1 excitability in the right hemisphere, where consolidation of ballistic thumb movements occurs [4,21]. This has been shown to take place via interhemispheric inhibition [14,24,25], which further enhances consolidation of ballistic movements. Thus, in the present study, we tested the hypothesis that consolidation of a ballistic movement is enhanced by dual-hemisphere tDCS over M1 compared with sham stimulation.

2. Materials and methods

2.1. Subjects

Twenty-eight healthy subjects (10 females and 18 males; mean age ± SD = 25.2 ± 2.7 years) participated in the study. The subjects were neurologically healthy and had no family history of epilepsy. The Human Research Ethics Committee at the national institute for physiological sciences approved all experimental procedures. All subjects gave informed consent before participating in the experiment.

2.2. Experimental procedure

The present study employed a single-blind, sham-controlled, between-group experimental design to compare the effects of tDCS or sham stimulation over M1 on performance of a ballistic thumb movement. The M1 was chosen as a target region because several previous studies have provided evidence that consolidation of newly learned ballistic movement involves M1 [4,27]. To measure consolidation of ballistic thumb movements, all subjects performed the same task at 1 h and 24 h after completing initial training.

The experimental procedure is shown in Fig. 1. First, all subjects underwent 20 trials of ballistic thumb movement to gain familiarity with the task. Next, the subjects performed 60 trials to measure their baseline performance before the application of tDCS. After baseline measurements, the subjects were randomly assigned to two groups (tDCS or sham), and all subjects performed four blocks (B1–B4) of the task while undergoing tDCS or sham stimulation. Each block contained 60 trials, and subjects performed a total of five blocks during training (total 300 trials). Trials were paced at 0.5 Hz. To avoid fatigue, a 2 min break was included between each block. In the tDCS group (14 subjects), stimulation of the anodal electrode over the right M1, and the cathodal electrode over the left M1, was applied for 25 min during the training. In the sham stimulation group (the remaining 14 subjects), tDCS electrodes were placed in the same position as the tDCS group, but stimulation was delivered for only the first 15 s. The subjects did not know whether they belonged to the tDCS or sham stimulation group.

At 1 h and 24 h after the initial tDCS or sham stimulation session, all subjects performed five additional blocks (B5–B9 and B10–B14) of the same task to examine the effects of interventions on consolidation of the trained ballistic movements.

2.3. Motor task

Peak acceleration of a thumb movement was used to measure ballistic thumb movement performance [4,21]. The subjects were seated in front of a computer screen. The position of a subject's left arm, flexed 70–80° at the elbow, slightly abducted the shoulder. The forearm was held in a neutral position (between pronation and supination) with the thumb free to move, whereas the fingers and forearm were fixed in place with a customized, upper-extremity orthotic. An accelerometer was then attached to the left thumb pad. The peak acceleration of each ballistic thumb movement was recorded with the accelerometer using integral electronics (model 25A; Endevco, CA, USA). The signal was amplified by a battery-powered, low-noise, signal conditioner (model 4416B Isotron Signal Conditioner; Endevco). Acceleration signals were amplified (10×) and digitized at 2000 Hz using an analog–digital converter and recorded on a computer for offline analysis. A customized LabVIEW program was created for triggering movement onset (with an auditory signal), providing visual feedback, and recording the motor performance data.

All subjects were asked to flex the thumb as rapidly as possible following the auditory signal. Acceleration signals were measured for 1.5 s after the auditory signal. At 1.5 s after the accelerometer value was obtained, the subjects were provided visual feedback regarding peak acceleration of the ballistic thumb movement via a computer screen that presented a color signal. When subjects performed faster than the median of the previous five acceleration values, a blue rectangle was presented on the computer screen. In contrast, when subjects performed slower than the median of the previous five acceleration values, a red rectangle was presented.

2.4. Transcranial direct current stimulation (tDCS)

A DC-Stimulator Plus (NeuroConn, Ilmenau, Germany) was used to deliver direct current through two sponge surface electrodes (surface area: $5 \times 5\,cm^2$) soaked with sodium chloride. The anodal electrode was placed over M1 in the right hemisphere, whereas the cathodal electrode was placed over M1 in the left hemisphere. The intensity of the stimulation was 1 mA. The fade-in/fade-out time was 15 s in both groups. In a preliminary experiment ($n = 6$), we compared the size of the motor-evoked potential (MEP) in the flexor pollicis brevis before and immediately after 1 mA anodal tDCS over right M1 and cathodal tDCS over left M1 for 25 min (for methodological detail of the MEP experiment, see Nitche and Paulus, 2000) [5]. Subsequently, the mean MEP amplitude of the right M1 significantly increased after tDCS (mean ± SE; 158.7 ± 22.0%, $P < 0.05$). Thus, the present tDCS protocol had a facilitative effect on cortical excitability of the right M1. For each participant, the location of M1 was identified using an individual T1 anatomical image and a frameless stereotaxic navigation system (Brainsight 2; Rogue Research, Montreal, Canada).

2.5. Data analysis

Peak acceleration of the ballistic thumb movement was analyzed as an indicator of motor performance. First, the median value of peak accelerations in each block was calculated. The median peak acceleration value of each block (60 trials) was normalized to the baseline measurement (such as B1/baseline and B2/baseline) and given a value of 1.0 as the baseline performance value. Improved ballistic movements at 1 h after training were calculated by dividing the value for the first block of training that began 1 h after initial training (B5) by that of the last block of initial training (B4) and multiplying the result by 100 (for example, B5/B4 × 100). Similarly, improved ballistic movements at 24 h after training were calculated by dividing the value of the first block of training that began at 24 h after initial training (B10) by that of the last block of training at 1 h after initial training (B9) (for example, B10/B9 × 100). The Wilcoxon rank-sum test was used to compare the rate of improvement for subjects in the tDCS group with that in the sham group because the data were not normally distributed.

In addition, a measure of overall skill acquisition was calculated (as the mean percentage change) by dividing the value of the last block of 24 h training (B14) by that the baseline measurement and multiplying the resulting value by 100 (B14/baseline × 100). The Wilcoxon rank-sum test was used to compare the overall skill acquisition value of the tDCS group with the sham group. $P < 0.05$ was considered statistically significant. Statistical analyses were performed using SPSS 21.0 software (SPSS, Chicago, IL, USA).

3. Results

The application of tDCS was safely completed in all subjects, with no adverse effects observed. For baseline measurement of the ballistic movement, the Wilcoxon rank-sum test revealed no significant difference between subjects in the tDCS and sham groups ($P = 0.16$). The mean peak acceleration in the baseline blocks prior to normalization was 3.74 ± 0.51 g (mean ± SE) for the tDCS group and 5.03 ± 0.72 g for the sham group. The normalized median accelerations in each block are shown in Fig. 2. The performance of the ballistic movement was gradually improved during the intervention in both the tDCS and sham groups (both groups; correlation coefficient $r > 0.97$, $P < 0.01$) according to a regression analysis that calculated correlation between number of training movements vs peak acceleration [4].

Improved performance of ballistic movement at 1 and 24 h after application of tDCS in the tDCS or sham groups is shown in Fig. 3. Improved motor performance observed at 1 h after training in both the tDCS and sham groups was not significantly different ($P = 0.69$; Fig. 3A). In contrast, the improvement in motor performance at 24 h after training was significantly greater in the tDCS group (mean ± SE; 144.2 ± 15.1%) than in the sham group (98.7 ± 9.1%, $P < 0.05$; Fig. 3B). These data indicate that motor training combined with tDCS enhances consolidation of ballistic movement at 24 h, but not 1 h, after training. The overall ballistic movement skill learning in the tDCS and sham stimulation group is shown in Fig. 3C.

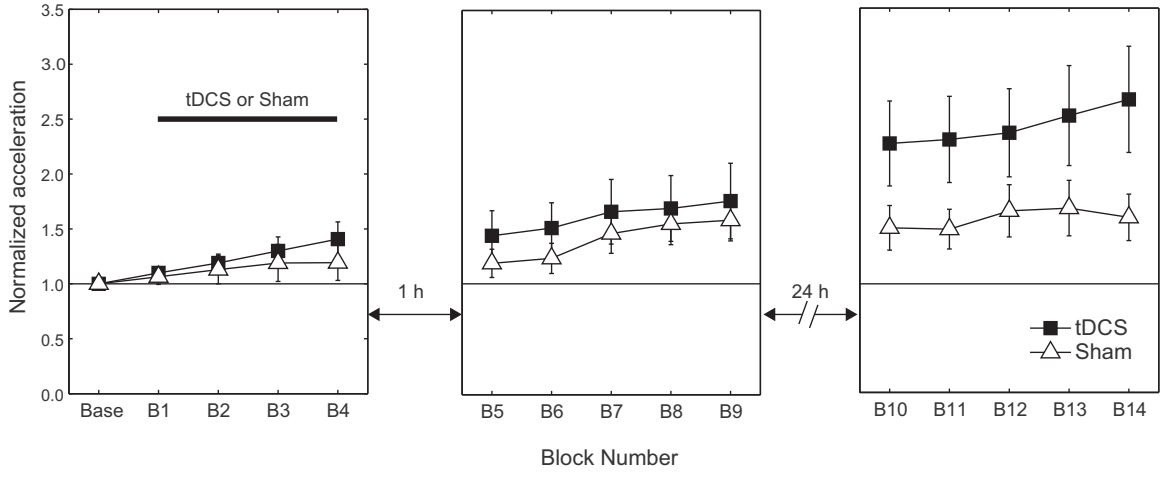

Fig. 2. Acquisition of a ballistic thumb movement.
The median of peak acceleration values was used to assess motor performance in each block. The mean value of motor performance was normalized to the baseline. Filled squares denote the tDCS group, and open triangles denote the sham stimulation group. Motor performance gradually improves in both the tDCS and sham groups. However, greater improvement in the ballistic finger movement skill is observed after training with tDCS than after training with sham stimulation. Bars represent standard error.

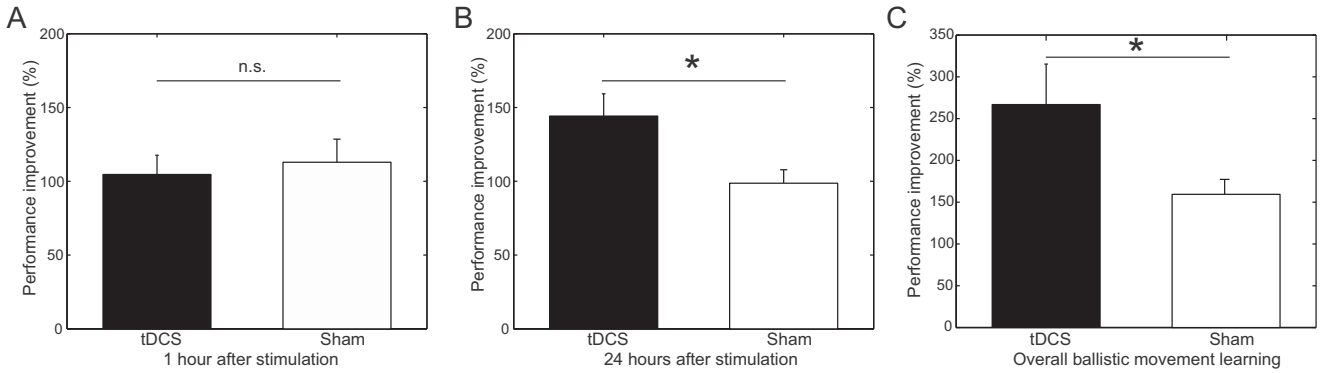

Fig. 3. Consolidation of performance and overall ballistic movement learning.
Effect of tDCS on consolidation of ballistic movements at 1 h and 24 h after initial training. No significant improvement in performance is observed 1 h after initial training in either group (A). In contrast, at 24 h after initial training, tDCS significantly enhances consolidation of the ballistic movement compared with after sham stimulation (B). The tDCS significantly enhances consolidation of a ballistic movement compared with after sham stimulation (C). Error bars represent standard error. $^*P < 0.05$.

Learning of this skill in the tDCS group (266.8 ± 48.4%) was significantly superior to that in the sham group (159.4 ± 17.8%, $P < 0.05$; Fig. 3C).

4. Discussion

Previous studies have reported that anodal tDCS over M1 enhances acquisition of various finger motor skills in healthy adults, including the visuomotor adaptation task [16], serial reaction time task [17], and sequential visual isometric pinch task [18,19].

Using a single-blind, sham-controlled design, the present study examined the effect of dual-hemisphere tDCS over bilateral M1 on consolidation of a ballistic movement. Results demonstrated that bilateral M1 tDCS also facilitated acquisition of a newly learned ballistic thumb movement, significantly improving peak acceleration of thumb movement compared with the sham group at 24 h after training. These data suggest that bilateral M1 tDCS enhances consolidation of newly learned ballistic thumb movements in healthy adults.

Results also demonstrated that tDCS facilitated performance of ballistic thumb movements at 24 h, but not at 1 h, after tDCS ended. There are two plausible explanations for this time-dependent effect of tDCS. It is possible that tDCS enhances sleep-dependent consolidation [17] because sleep is reportedly necessary for consolidation of some types of motor skills [28–31]. The consolidation of motor skill acquisition during sleep appears to rely on covert reactivation of brain areas involved in motor skill acquisition [32]. Anodal tDCS over M1 was previously reported to facilitate improvement of a serial reaction time task 24 h after tDCS ended [17]. Thus, M1 tDCS may enhance sleep-dependent consolidation. However, it is also possible that tDCS enhances consolidation independent of sleep [18]. A previous study reported that tDCS affected sleep-independent consolidation of a sequential visual isometric pinch-force task [18]. Thus, the tDCS protocol in the present study may have enhanced this time-dependent consolidation of ballistic finger movement. However, resolving this issue will require further experiments that include sleep as an independent variable.

In the present study, we found that a dual-hemisphere tDCS protocol facilitated consolidation of a ballistic finger movement, which was consistent with a previous study showing that dual-hemisphere tDCS over bilateral M1 enhanced consolidation of a sequential finger movement task [33]. In our dual-hemisphere tDCS protocol, the anodal tDCS might have increased excitability of M1 in the right hemisphere, where the consolidation of ballistic thumb movements occurs [4,21]. In addition, decreased excitability in the left hemisphere M1 by cathodal tDCS might have further increased excitability in the right hemisphere M1 through a reduction in interhemispheric inhibition [10,14,24,25]. We speculate here that the combined effect of increasing M1 excitability in the right hemisphere by anodal tDCS and decreasing M1 excitability in the left hemisphere by cathodal tDCS may underlie the behavioral gain observed.

In the present study, we used only a dual-hemisphere tDCS. Thus, we cannot rule out the possibility that a single-hemisphere tDCS over M1 might have been sufficient to improve consolidation. In a preliminary experiment with six healthy subjects, we investigated the effect of single-hemisphere tDCS (the anodal electrode over the right M1 and the cathodal electrode over the contralateral orbit) on consolidation in the same ballistic movement task. However, we did not observe any significant performance improvement compared with sham stimulation. Therefore, it is reasonable to consider that anodal tDCS over the M1 alone might be insufficient to induce the behavioral improvement observed in the present study. Future studies should clarify this issue by investigating single-hemisphere stimulation-induced effects on behavior.

There were some limitations to this study. First, a single-blind design was used; future studies should employ a double-blind design to avoid the observer effect. Second, we investigated the effect of tDCS on performance of a trained task only. In future studies, it would be important to examine a generalization of tDCS effects on performance of untrained tasks. Third, we stimulated only one brain region. The lack of other control regions to be stimulated could limit the strengths of our results when relatively lower spatial resolution of tDCS is taken into account. Finally, we investigated only the behavioral changes induced by tDCS. Future studies will be required to examine the neurophysiological changes associated with the behavioral gain observed in this study. Nevertheless, loss of thumb movement remains a problematic impairment after stroke [34,35]. Thus, our findings may be useful in guiding the rehabilitation of patients with upper limb dysfunctions following subcortical strokes.

5. Conclusion

The present study showed that dual-hemisphere tDCS over bilateral M1 enhances the consolidation of a ballistic thumb movement.

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